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Snow Cover Variability in Great Britain during a Changing Climate

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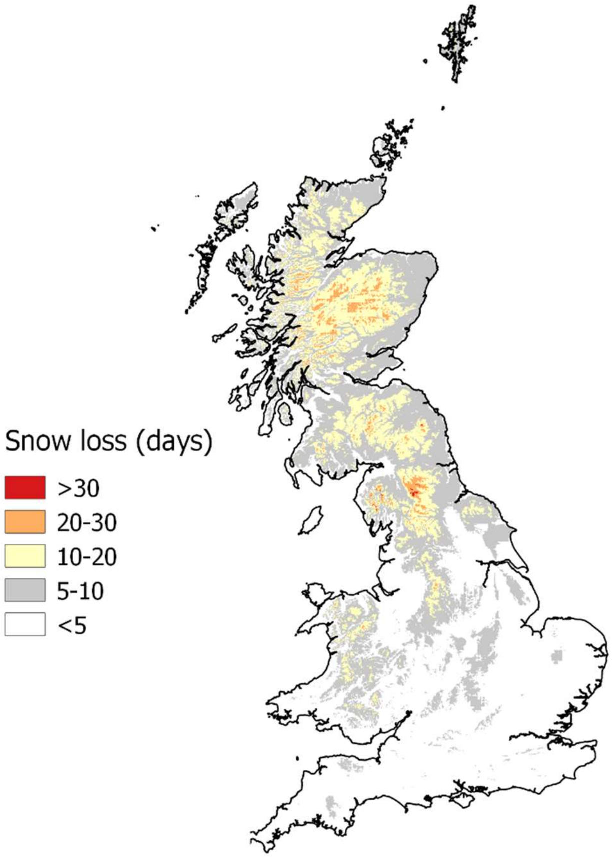
Highlights

- *Average annual snow cover duration has a strong general relationship with mean temperature, best defined as a non-linear logistic curve*
- *A general trend of declining average snow cover has been mapped for GB, although snow cover duration also shows considerable interannual and multi-year variability that can be related to prevailing synoptic conditions*
- *Mountain areas have different patterns of variability compared to lowlands*



Reduction in average GB snow cover between 1960-1980 and 1990-2010

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Snow Cover Variability in Great Britain during a Changing Climate

Introduction

Snow provides many of us with vivid memories of the capricious nature of weather, albeit from rather different perspectives. Especially for the unprepared, snow can cause severe social and economic impacts including disruption to transport, business, agriculture, and everyday activities. Yet snow can also be remembered or even anticipated with fondness due to qualities that extend beyond its direct appeal to winter-sport enthusiasts (Figure 1). The transformation of the landscape during snow cover has been characterised and celebrated in many ways through culture, folklore and the arts.

Although the occurrence of falling snow is an important aspect of this meteorological relationship, it is the presence of snow cover on the ground over varying durations that causes the more significant human as well as biological and physical impacts. In the latter case, snow can act as insulator and protector of soil and vegetation from severely cold air, meaning its presence can be a key factor in biogeography and biodiversity. Snow cover can also have a fundamental role in the earth's albedo and energy balance, and, depending on its duration, also act as a crucial influence in the hydrological cycle and the seasonal flow of rivers.

The sensitivity of snow cover duration and extent to climate factors mean that potentially it can provide a very good indicator of climate change. Long-term changes in snow cover have major implications for the natural and human world with effects extending far beyond snow-covered regions. In the Northern Hemisphere, recent analysis has identified a dominant trend for declining snow cover that can be related to rising temperatures (Brown and Mote, 2009; Fontrodona et al., 2018). However, anomalies in this general pattern exist, apparently related to local and regional climate factors: these are most often attributed to increased precipitation rates at higher elevations or upper latitudes where temperatures remain low enough for precipitation to primarily occur as additional snowfall.

This article evaluates the current state of knowledge for general snow cover trends and variability in Great Britain (GB), and follows a previous convention by defining the annual period of interest (the 'snow year') as from October-May. This period of analysis is therefore distinct from, but complementary to, that used for the regular annual summer/autumn surveys of isolated snow patches that may survive at topographically-favoured mountain locations (e.g. Watson et al., 2009; Cameron, 2018; Cameron and Watson, 2019).

The oceanic climate of GB means it occupies a particularly interesting position for interpreting snow cover variability (Manley, 1952). Snow cover in lowland areas is usually rather ephemeral but there is often a notable contrast with mountain areas that typically have a much longer snow cover due to lower temperatures and higher precipitation rates (Figure 2). In addition to topographic effects, marked variations in snow cover can occur on both west-east and north-south gradients due to contrasting oceanic against continental influences on local weather patterns. Consequently, considerable variability can occur from year to year, as recently shown by the relatively snowless 2018-2019 year, compared to the snowier 2017-2018 year which featured a notable late cold spell (Galvin et al., 2018). Instrumental records and folklore also record rather more widespread snowy years from the past, notably 1946-1947, 1962-1963 and 1978-1979 when snow cover was extensive at lower levels. However, a further feature of the GB snow climate is marked by occasional years, notably 1966-1967 and 2013-2014, when there were very large snow accumulations and hence an extended snow-lying season in some mountain areas, despite there being much less snow at lower levels. These complex variations suggest it may be over-simplistic to infer the same pattern of change for all regions and elevations.

Snow-cover observations and models

A key issue for interpreting snow cover variability is data availability. At manned stations, the UK Met Office (UKMO) method has been to record a day of snow cover if at 0900GMT the observer noted more than 50% of the surrounding ground at a similar elevation was snow covered. Data can then be aggregated into annual days of snow cover at that location and then longer-term time series (e.g. Eskdalemuir: Figure 3), although unfortunately station changes and increased use of automation means that continuing long-term records are rare. Another comprehensive data source is provided by regular station reports from the Climatological Observers' Link (COL). As explained below, aggregated station data have also been used to derive general GB snow cover maps. However, a significant problem has been the sparsity of stations above 300m elevation meaning that information on patterns of snow cover variability in the uplands has been limited.

Another archived data source is the Snow Survey of Great Britain (SSGB), which operated in various guises from 1937 to 2007. The SSGB aimed at provided more representative data at different elevations, especially for upland areas, and was originally directed by eminent climatologist Gordon Manley. Data was derived from daily observations made by volunteers across a range of diverse occupations (e.g. estate workers, forestry, water utilities etc.) and included both snow cover presence at the base station and of the typical snowline (to the nearest 150m elevation: see Figure 2) on the adjacent mountains (Spencer et al., 2014). An annual SSGB report was produced by UKMO between

1954-1992, providing a general synthesis (available from UKMO, 2019). Although the SSGB is now discontinued, local snow surveys have continued to be published, including from Fairfield (Cumbrian Fells: Johnson, 2005) and from the western Cairngorms using automated repeat photography (Andrews et al., 2016). It should be noted that all these observed data contain a subjective component regarding presence of 'snow cover' and are susceptible to potential observer biases, as may occur with an over-emphasis on specific aspects (e.g. N-facing slopes), perhaps more so for the volunteer-based SSGB.

Concurrently, there has been a growing interest in the use of satellite remote sensing data, using both visible and microwave spectra. However, although remote sensing is providing important advances for understanding large-scale patterns of snow cover change, there remain significant challenges, including cloud cover problems for visible spectra and resolution issues for microwave in regions of variable snowpack (Bormann et al., 2018). These challenges are most pronounced for locations such as GB which are characterised by frequent cloud cover and highly-variable snow cover related to terrain, especially in the uplands. This identifies a continuing need for ground-based data to provide independent corroborative data sources.

Observed data may also be used to calibrate and test models that can infer general patterns of snow cover change. Energy-balance models are usually data-intensive and more suited to local studies meaning that the use of simpler models has been preferred for large-scale analysis. These simple models include empirical models based upon inferred statistical relationships with climate data, as described below, or degree-day models that simulate patterns of snow accumulation and melt which are often used in hydrology (e.g. Bell et al., 2016).

Average snow cover: regional patterns

Aggregated station observations can be used to derive maps of annual snow-cover days and long-term average snow-cover days. Hence, Manley (1939) used UKMO data to produce an average GB snow cover map based on a relationship between winter monthly mean temperatures and snow cover, subsequently refined by Jackson (1978) for a later period by using data from the SSGB. More recently, automated routines have allowed gridded data to be interpolated from station records as utilised for the GB snow cover maps produced for the National Climate Information Centre (see https://www.metoffice.gov.uk/public/weather/climate/). However, as highlighted earlier, the scarcity of upland stations in the UKMO database is an important constraint, and these maps do not provide information on locations with longer snow durations (>60 days/year). By contrast, analysis of SSGB data at specific upland locations, including at Ben Lawers (southern Scottish Highlands; Trivedi et al., 2007) and several sites across Scotland (Spencer et al., 2014) has suggested rather different patterns of snow cover duration for mountain areas.

Archived SSGB data extending from the Brecon Beacons to Scottish Highlands has recently been used to further investigate altitudinal and geographic variations in average annual snow cover through a general relationship with mean temperature (Brown, 2019). This work used a standard lapse rate to interpolate mean temperature at the same location and elevation as SSGB snow cover data (base station, 750m and summit elevation). Investigation showed that a logistic (non-linear) regression function was more appropriate than linear regression and this yielded a distinctive sigmoidal relationship for the 2 variables (Figure 4), plotting snow cover duration as a fraction of the snow year (i.e. total cover of 1.0 = 243 days). This logistic function also seemed to be invariant with time and is consistent with similar analysis from the Alps (Hantel and Hirtl-Wielke, 2007). This suggests a general relationship which can then form a useful basis from which to map and contextualise snow cover change for both uplands and lowland. Using this approach, Figures 5(a) and (5b) show regional variations for two recent time periods and a general decline in average snow cover for GB over the last 30 years (Figure 5c).

The same analysis seemed to find no significant relationship for average annual snow cover based upon precipitation, either expressed as total precipitation or inferred snowfall precipitation (Brown, 2019). However, this may also be related to the difficulties incurred in accurately measuring and interpolating precipitation for the uplands, especially when estimating snowfall amounts.

The exact form of the logistic curve in Figure 4 should be regarded as tentative pending further corroboration. However, its basic shape may be used to help contextualise previous work that described altitudinal gradients for snow cover duration, as these gradients would be expected to represent a temperature lapse rate relationship at the relevant locations. For example, Jackson (1978) inferred an exponential increase in snow cover duration up to 400m and a linear increase above this elevation, which is consistent with the right half of the logistic curve; however, the notional 400m threshold may also vary depending on local temperature influences such as latitude and oceanicity. Similarly, observations suggesting steeper altitudinal increases in snow cover for northern compared to southern GB regions can be referenced as comparing a zone representative of the centre of the logistic function with a zone to the right. These observations (Harrison, 1993; Stirling, 1997; Trivedi et al., 2007) include rates of increase of 5 days/100 m in Wales and central England compared to 15–20 days/100 m in Scotland. Altitudinal increases have also been noted to vary from 20 days/100 m in snowy colder years to less than 10 days/100 m during milder winters, and to be more linear in colder winters compared to nonlinear in warm ones (cf. Harrison et al., 2001). Again, this is consistent with different temperature zones on the logistic curve.

The logistic curve therefore highlights a higher climate sensitivity zone at 0-4°C mean temperature (Oct-May) where annual snow cover duration loss (or gain) occurs at a faster rate. This appears consistent with previous analysis that has suggested maximum snow cover sensitivity occurs at specific altitudes, including at 400 ± 100 m (Harrison et al., 2001) and 750 m (Trivedi et al., 2007). These different altitudinal interpretations of maximum sensitivity may be accounted for by geographic variations in local temperature profiles that mean that the zone of higher sensitivity can occur at different elevations across GB.

The higher sensitivity zone at 0-4°C mean temperature is therefore defined by multiple geographic factors, notably latitude, elevation, and coastal adjacency (oceanicity). A particularly noteworthy example is shown by those upland areas of N England that have lost ca. 30 days in average snow cover for the more recent period compared to 30 years earlier (Figure 5c). During an era of increasing temperatures, locations entering the high sensitivity zone will tend to experience a more rapid change in annual snow cover compared to the past. This suggests the need for focussed monitoring in such locations to help identify and address the ecological, hydrological, and socioeconomic implications.

Year to year variability

The long-term record from Eskdalemuir (Figure 1) is notable for its considerable variability in snow cover, both interannually and through multi-year phases. This site has an October-May mean temperature (5°C for 1981-2010) that positions it above the zone of high sensitivity noted above. Hence, although a small long-term trend towards declining snow cover can be detected, the much more dominant pattern is the confounding effect of shorter-term variability.

Recent research has also investigated these shorter-terms patterns of variability in GB snow cover. It is here that the influence of variable precipitation sources may become more influential in individual snow years than found with average annual snow cover, by modulating the general temperature to snow cover relationship. Spencer and Essery (2016) used SSGB Scotland data to investigate the relationship of snow cover duration with the winter North Atlantic Oscillation (NAO) index, finding a negative relationship that was strongest for coastal lowland locations. A positive NAO index with dominant westerly airflow and generally milder winters therefore generally produces less snow cover than negative NAO index winters that have an increased frequency of colder anticyclonic conditions.

Similarly, Brown (2019) used the SSGB to investigate interannual variability for both upland and lowland locations compared to synoptic-level atmospheric patterns represented by the NAO index and frequency of Lamb Weather Types. This study found that although longer snow cover duration in the lowlands was strongly associated with easterly-type airflows, indicating prolonged incursion of polar continental air, this pattern was less evident in mountain locations with the exception of those particularly exposed to winds from that easterly direction. Instead, an increased frequency of N and NW airflow types was highlighted for extended snow duration in major mountain areas: these weather types are notably associated with polar maritime and arctic air, with a high frequency associated with anomalous snowy years at higher elevations (e.g. 1966-1967). Anomalously large mountain snow depths and extended snow durations can also occur when returning polar maritime air is combined with a high frequency of cyclonic-type conditions, as occurred in winter 2013-2014. Considerably greater snow durations at higher elevations are often a consequence of higher lapse rates that are a feature of polar maritime air; in 2013-2014 snowfall and snow cover at lower elevations were notably limited compared to the huge accumulations occurring in much lower temperatures above 600m.

It interesting to note a similar distinction between maritime and continental airflows has been derived based upon snowpack observations for avalanche recording, with deeper more bonded and stable snowpacks associated with polar maritime airflows (Kendon and Diggins, 2018). As most GB mountain ranges are in westerly or northerly situations, these ranges have the potential for large snow accumulations from cold-moist polar maritime airflows, especially when enhanced through orographic effects, by comparison to more gradual accumulations due to colder drier air from easterly continental sources. Extremely snowy years also show a good correspondence with following summers having a large depth and extent of snow in surviving patches, as for example with summer 2014 (Cameron et al., 2015).

These synoptic-scale influences act in combination with local topography and relative exposure of different mountain ranges to airflow directions which is typically related to their position adjacent to, or inland of, the respective coastline. For example, Johnson (2005) noted the association of snow cover on the Cumbrian Fells with NW/N airflows rather than NE airflows, consistent with their west coast location. As a consequence, it appears that some mountain ranges may have different synoptic relationships when compared to the adjacent lowlands regarding the influence of dominant seasonal circulation patterns, including against aggregate measures such as the NAO index. It has therefore been suggested, based upon archived SSGB data, that a positive NAO index may have been associated with increased snow duration on some GB mountains (Brown, 2019) although whether this relationship still persists is unknown. Nevertheless, these topographic and synoptic-scale interactions, often occurring on a multi-year as well as interannual timescale, may explain apparently anomalous trends found in shorter time-series data, as with the recent observations of increasing snow cover in the western Cairngorms (Andrews et al., 2016).

The Future

A general finding for a strong inverse relationship with mean temperature means that we can infer with reasonably high confidence that there will be an ongoing long-term decline in average snow cover duration as climate warming continues (a sample projection based upon an ensemble mean temperature change for the 2041-2060 period from the UK Climate Projections 2018 is provide in Supplementary Material) . The actual reduced duration of average snow cover and its dependence on the rate of future temperature increase will ultimately be an outcome of feedbacks in the climate system and its response to changing concentrations of greenhouse gas emissions.

Although we may derive an unequivocal conclusion for continued future declines in GB snow cover, the continued occurrence of infrequent snowy episodes also remains possible, especially for some upland locations with distinctive exposures. As highlighted above, prolonged snowy years have a good association with relative exposure to the frequency of particular synoptic atmospheric patterns. As yet, climate models have less confidence in simulating future changes in frequency of such synoptic patterns and how they might be modified by climate warming. At lower levels, snow cover associated with the incursion of cold polar continental and arctic airmasses is likely to continue but to become increasingly short-lived. However, the possibility remains that longer duration snow cover continues to occur in GB mountain areas, notably those to north and north-west. These conditions may be particularly associated with increased annual frequency of polar maritime air when the right combination of heavy snowfall and lower temperatures may prevail to allow extended snow durations. Further work to is required to investigate the relative likelihood of changes in such synoptic patterns and hence their implications for sensitive locations.

Future trends and patterns of change imply profound changes for the natural environment, requiring more comprehensive monitoring and research beyond the few existing focal sites (Kay, 2016). In socioeconomic terms, reduced snow-related disruption will have significant benefits for some locations, notably for marginal hill-farming areas. By contrast, Scotland's ski centres are very likely to experience a declining duration of natural snow cover despite the possibility of occasional good years. Indeed, the likelihood exists that in future the increased rarity of snow in the lowlands means that its novelty appeal encourages people to travel to the mountains to renew the uniqueness of the experience when it does occur, as occurs now in countries such as Spain and Portugal.

A Role for Citizen Science?

Enhanced understanding of snow cover variability clearly requires improved observation data to help decipher both interannual and multi-year variations in the context of long-term trends, especially for the uplands. Increased availability of remote sensing data provides one means to achieve this goal, but as discussed satellite remote sensors encounter difficulties in complex terrain.

Ground observations therefore have continued relevance. In addition to UKMO and COL stations, enhanced snow cover data could be facilitated through a wider network of snow observers. The original SSGB was a volunteer-based initiative, whilst current summer/autumn snow-patch surveys are organised by volunteer enthusiasts (e.g. Cameron and Watson, 2019). Citizen-science climate initiatives have already successfully enhanced data availability, including archived sources (e.g. Ben Nevis Weather Observatory logbooks) and phenology records (e.g. 'Nature's Calendar').

Scope exists therefore for a broader citizen science initiative to record and monitor presence of snow cover, following the original SSGB vision, with synthesis allowing interpretation between local, national and global patterns of change. In addition to snow cover presence at specific locations, this could include snowline elevation on prominent mountain peaks acting as local landmarks (Figure 2). New data could also allow further comparison of general snow cover patterns with the data collated from summer/autumn snow-patch monitoring.

Conclusion

The general fascination for snow-covered landscapes can provide an important cue to help interpret the wider implications of our changing climate. Average annual snow cover patterns and trends show a strong relationship with mean temperatures. For most years in the future it can be inferred that GB snow cover durations beyond a few temporary days will become increasingly confined to northerly upland and mountain areas. However, snow cover patterns are also characterised by large inter-annual variability that can be related to prevailing large-scale atmospheric patterns and local variations in precipitation. This intrinsic variability highlights the potential for misinterpretation of snow-cover changes based upon incautious selection of start and end years or averaging periods, notable pitfalls of 'noisy' time-series data. Evidence also suggests that different patterns of variability occur at higher altitudes due to differences in combined meteorological influences. Improved data are required to further investigate these changing relationships and their wider implications for climate change adaptation.

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References

Andrews, C., Ives, S., Dick, J. 2016. Long-term observations of increasing snow cover in the western Cairngorms. *Weather*, **71**, 178–181

Bell, V.A., Kay, A.L., Davies, H.N., Jones, R.G. 2016. An assessment of the possible impacts of climate change on snow and peak river flows across Britain. *Climatic Change*, **136**, 539–553.

Bormann, K.J., Brown, R.D., Derksen, C. and Painter, T.H. 2018. Estimating snow-cover trends from space. *Nature Climate Change*, **8**, 924–928.

Brown, I. 2019. Snow cover duration and extent for Great Britain in a changing climate: altitudinal variations and synoptic-scale influences. *International Journal of Climatology doi:10.1002/joc.6090*

Brown, R.D. and Mote, P.W. 2009. The response of Northern Hemisphere snow cover to a changing climate. *Journal of Climate*, **22**, 2124–2145.

Cameron, I. 2018. Snow patches in England and Wales during spring and summer 2018. *Weather*, **73**, 333-334.

Cameron, I., Watson, A. 2019. One Scottish snow patch survives until winter 2018/2019. *Weather*, **74**, 253-255.

Cameron, I, Watson, A, Duncan, D. 2015. Twenty one snow patches survive until winter 2014/15. *Weather*, **70**, 314–316.

Fontrodona Bach, A., van der Schrier, G., Melsen, L.A., Klein Tank, A.M.G., Teuling, A.J. 2018. Widespread and accelerated decrease of observed mean and extreme snow depth over Europe. *Geophysical Research Letters*, **45**, 312–319.

Galvin, J., Kendon, M., McCarthy, M. 2019. Snow cover and low temperatures in February and March 2018. *Weather*, ***74***, 104-110.

Hantel, M., Hirtl-Wielke, L.M. 2007. Sensitivity of Alpine snow cover to European temperature. *International Journal of Climatology*, **27**, 1265–1275.

Harrison S J. 1993. Differences in the duration of snow cover on Scottish ski-slopes between mild and cold winters. *Scottish Geographical Magazin*e, **109**, 37-44.

Harrison, S.J., Winterbottom, S.J. and Johnson, R.C. 2001. A preliminary assessment of the socio-economic and environmental impacts of recent changes in winter snow cover in Scotland. *Scottish Geographical Journal*, **117**, 297–312.

Jackson, M. 1978. Snow cover in Great Britain. *Weather*, **3**, 298–309.

Johnson, P. 2005. Snow-cover on the Cumbrian Fells. *Weather*, **60**, 132–135.

Kay, A.L. 2016. A review of snow in Britain: the historical picture and future projections. *Progress in Physical Geography*, **40**, 676–698.

Kendon, M., Diggins, M. 2018. Severe weather and snow conditions on Cairngorm summit in February to March 2018. *Weather*, **74**, 98-103.

Manley, G. 1939. On the occurrence of snow-cover in Great Britain. *Quarterly Journal of the Royal Meteorological Society*, **65**, 2–27.

Manley, G. 1952. Climate and the British Scene. London: Collins.

Spencer, M., Essery, R. 2016. Scottish snow cover dependence on the North Atlantic Oscillation index. *Hydrological Processes*, **47**, 619–629.

Spencer, M., Essery, R., Chambers, L., Hogg, S. 2014. The historical Snow Survey of Great Britain: digitised data for Scotland. *Scottish Geographical Journal*, **130**, 252–265.

Stirling, R. 1997. The Weather of Britain. London: Giles de la Mare.

Trivedi, M.R., Browne, M.K., Berry, P.M., Dawson, T.P., Morecroft, M.D. 2007. Projecting climate change impacts on mountain snow cover in central Scotland from historical patterns. *Arctic, Antarctic and Alpine Research,* **39**, 488-499.

UKMO, 2019. Snow Survey of Great Britain. https://www.metoffice.gov.uk/research/library-and-archive/archive-hidden-treasures/snow-survey

Watson, A., Davison, R.W., Pottie, J. 2002. Snow patches lasting until winter in north-east Scotland in 1971–2000. *Weather*, **57**, 374–384.

Figures

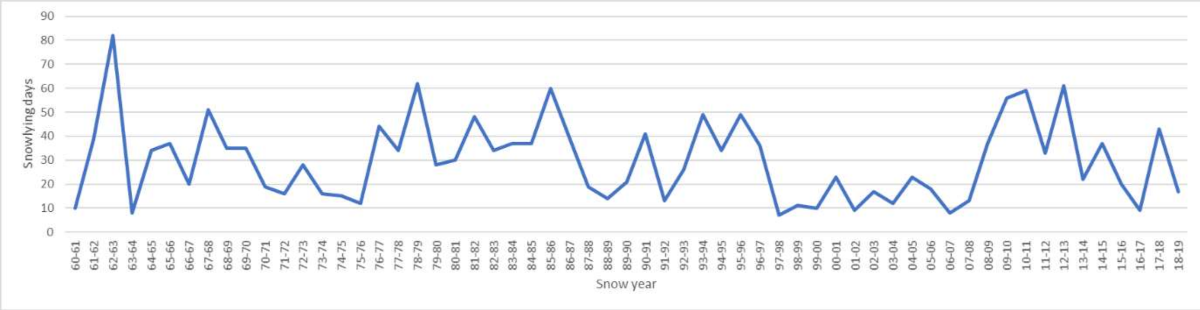
Figure 1. A snow-covered landscape in the northern Cairngorms, the snowiest area of GB

Figure 2. A well-defined snowline on Ben Nevis and Aonach Mor (at ca.750m altitude)

Figure 3. Eskdalemuir annual days of snow cover (Oct-May ‘snow year’) since 1960

Figure 4. Non-linear relationship between snow cover duration and mean temperature (Oct-May) defined by best-fit logistic regression based upon SSGB data (after Brown, 2019)

Figure 5. Average GB snow cover duration inferred using the relationship in Figure 2 for 20-year periods: (a) 1960-1980 (b) 1990-2010 (c) change between 1960-1980 and 1990-2010



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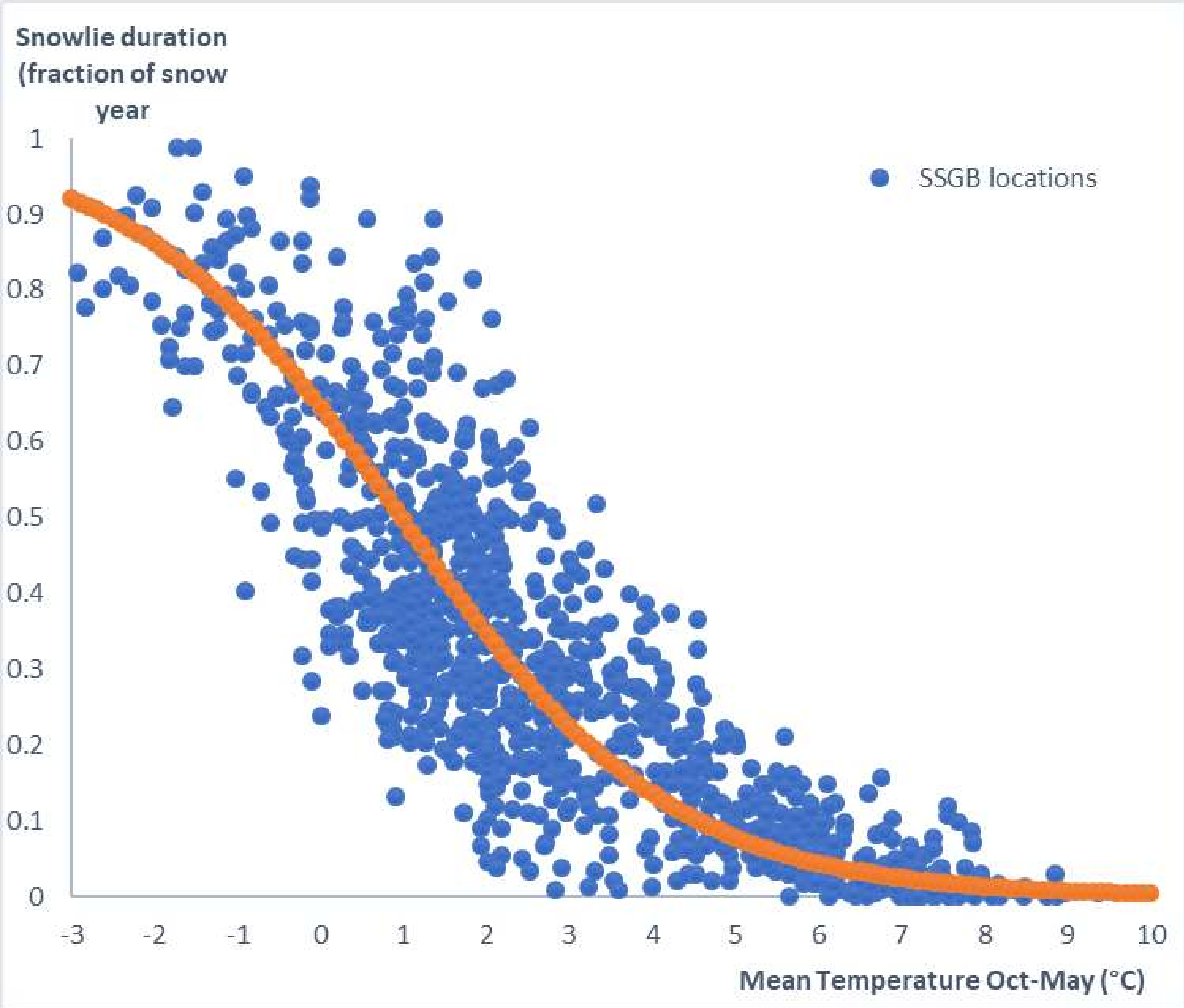

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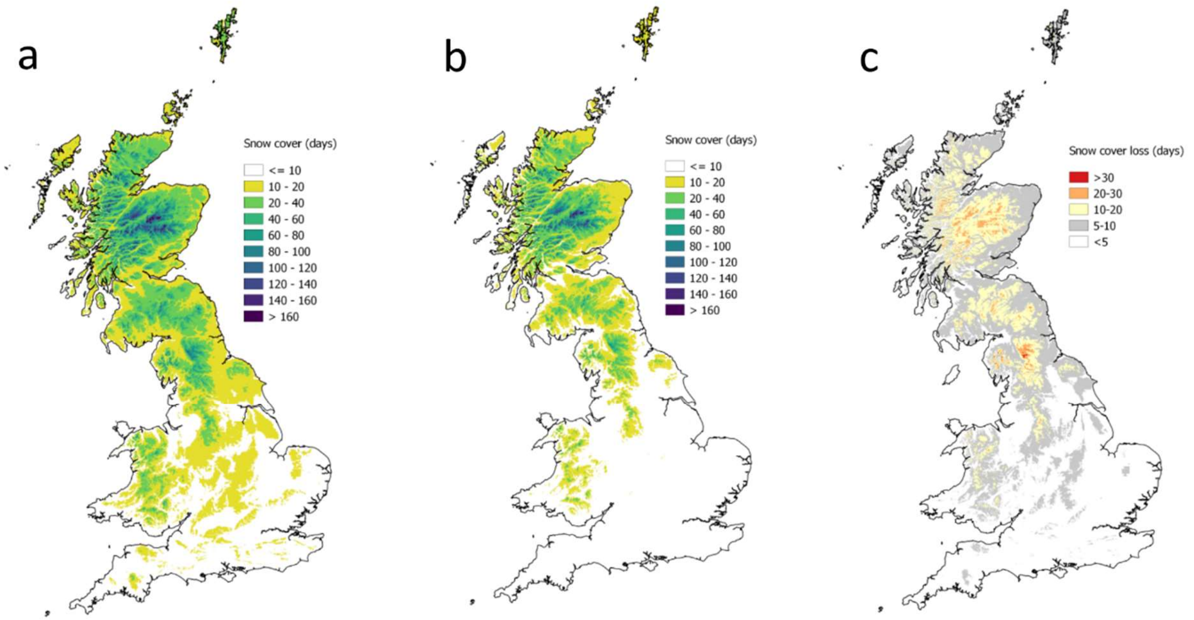

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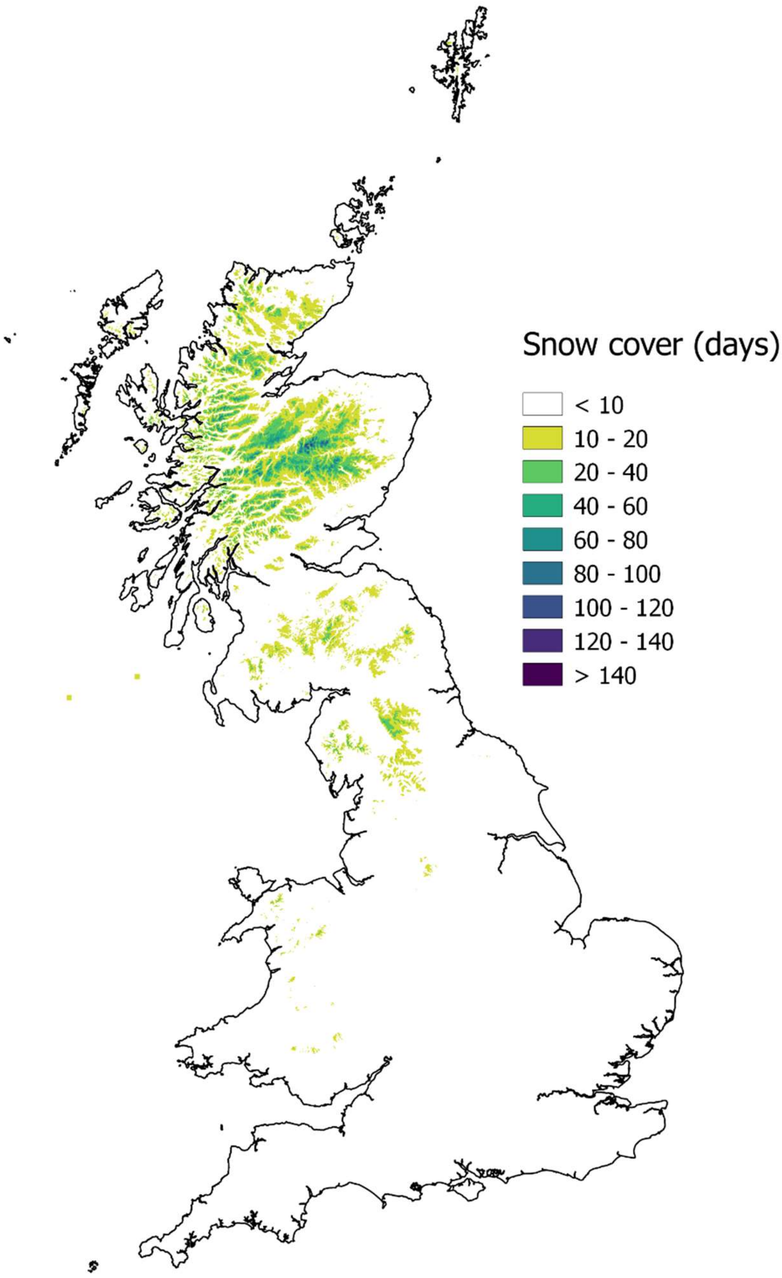

Supplementary Material. Future 'central estimate' projection of snow cover for the 2041-2060 period based upon the logistic curve for snow-cover to mean temperature relationship (Figure 4). This 'central estimate' is based upon the mean of data from the ensemble of 12 HadGEM/HadREM model runs used to provide regional detail in the UK Climate Projections 2018 (see https://ukclimateprojections.metoffice.gov.uk).
NB. Further downscaling to 1km has been applied using a delta-change method using the local detail provided for the baseline period (main paper: Figure 5) to show relationship with local topography (see Brown, 2019, for further explanation).